Research Article

Effect of Curing Time on Bond Strength between Reinforcement and Fly-ash Geopolymer Concrete

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Received: 13 December 2019; Revised: 14 February 2020; Accepted: 18 February 2020; Published online: 17 March 2020

Abstract

This paper focuses on showing the effect of curing time on the bond strength between reinforcement and fly-ash geopolymer concrete. Various parameters are varied to compare between ordinary Portland cement (OPC) concrete and Class C fly-ash geopolymer concrete (GPC). These concretes are designed to have two different compressive strengths, and each of them is cured at 28 and 56 days. The diameter of reinforcement is selected as 12 and 16 mm with deformed type. From the study, it is found that the bond strength increase with increasing the compressive strength, while with decreasing the diameter of reinforcement, as expected. The bond strength of OPC embedded with smaller reinforcement is more sensitive to the increase of the curing time. However, its bond strength is significantly less sensitive to the compressive strength. The bond strength of GPC with higher design compressive strength is more sensitive to the increase of the curing time. However, its bond strength is significantly less sensitive to the diameter of reinforcement.

Keywords: Bond strength, Deformed bar, Concrete, Fly-ash based geopolymer, Curing time

1 Introduction

Concrete has widely been considered as one of the most favorite construction materials for a long period of time due to its ease in shaping and so on. Nevertheless, many researches have been done so as to find an optional material for various reasons, such as supporting the growth of construction in cities as well as countries.

Currently, one of the problems mentioned all over the world was concerned with global warming [1], [2]. Cement, which is an important ingredient in concrete, was considered as related to the global warming problem [3]. This was due to the fact that the emission of greenhouse effect gas (GHG) in terms of CO_2 [4] occurred in the process of cement production. It is estimated that the manufacture of a kilogram of cement was able to cause about a kilogram of CO_2 [5]. Andrew [6] stated that in 2016, the manufacture of cement would cause the emission of CO_2 by 1450 Mton which was equivalent to 8% of the emission of CO_2 in the world. If the construction is deducted, the emission of CO_2 could possibly be reduced as much. However,

Please cite this article as: A. Petcherdchoo, T. Hongubon, N. Thanasisathit, K. Punthutaecha, and S.-H. Jang, "Effect of curing time on bond strength between reinforcement and fly-ash geopolymer concrete," *Applied Science and Engineering Progress*, vol. 13, no. 2, pp. 127–135, Apr.–Jun. 2020.

this was quite difficult in the current situation, because all the countries needed constructions to support their economics [5]. It was also impossible to ignore this problem. As a result, one of the remedial options was to balance all the problems by following the concept of sustainability which comprised environment, society, and economy. There were two main methods to attain this concept [7]; repairs of concrete structures, and use of sustainable materials [8], [9]. One of the options for sustainable materials is to use waste in activities [10].

Geopolymer could be an answer for the issue. In recent times, a cementless binder for producing concrete, termed as geopolymer concrete, was quickly gaining popularity in concrete research work as the technology eliminated the need for cement [11]. Sarker [12] reviewed that geopolymer was a type of alumino-silicate product which could provide good bonding properties. There are several types of geopolymer, for instance, metakaolin based, fly-ash based, etc. They serve as the source of aluminium and silicon which react with another substance which serves as a source of alkali. Metakaolin seemed to be paid more attentions as a replacement for cement [13], [14]. However, if the concern is about the emission of CO_2, the metakaolin-based geopolymer might not be an appropriate option. This is due to the fact that the production of metakaolin required calcinating high-purity kaolin clay [15]. Hence, high energy is required in the calcination process which can cause CO_2 emission.

Fly-ash (FA), which is a by-product from coal power plants, was known as one of the wastes causing environmental impacts in the form of air and water pollution [16]. Moreover, it was found that the amount of fly-ash production increased rapidly, up to 600 million tons per year [17]. In the past, one of the ways to manage fly-ash was to put it as landfills. However, this management method might not be suitable for the situation of excessive amount of fly-ash. One of the methods to reasonably remedy the issue was to reuse fly-ash in concrete [16]. Therefore, the study of its properties has been carried out, such as compressive strength, chloride resistance, and so on [18], [19].

One of the topics to be considered in reusing fly-ash is producing concrete called geopolymer concrete. The name "fly-ash geopolymer" was used for the chemical reaction between fly-ash and alkaline liquid in a polymerization process [20]. This reaction can be named as "geopolymerization" which could refer to the hardening of fly-ash based geopolymer. This occurred due to the dissolution of aluminium and silicon in fly-ash via alkaline activators [21]. Such geopolymer was reported to possess several desirable characteristics, such as fire resistance, dimensional stability and acid resistance, as well as repaid development of mechanical strength and excellent adherence to aggregates [22], [23]. Several researches have been conducted in order to determine the aforementioned characteristics of fly-ash based geopolymer concrete. Soutsos *et al*. [24] found that alkali-activated FA required elevated curing temperatures and high alkali concentrations. The most important factor affecting the reactivity was the particle size of FA. Görhan *et al*. [21] studied the effect of curing on the properties of geopolymer paste consisting of fly-ash mixed with metakaolin ranging from 10% to 40%. The samples were subjected to curing at 60°C and 80°C for 2, 4 and 24 h. It was found that the ideal curing conditions were 60°C and 2 h for producing geopolymer paste. Moreover, the compressive strength of the samples subjected to that curing condition reached up to 25.1 MPa, and a 40% metakaolin substitution provided a better geopolymerization and significantly improved compressive strength.

To study the bond strength between reinforcement and fly-ash geopolymer concrete, Castel and Foster [25] investigated geopolymer concrete bond with both deformed and smooth reinforcing steel bars using the standard RILEM pull-out test, considering different heat curing conditions. The geopolymer binder was composed of 85.2% of low calcium fly-ash and 14.8% of ground granulated blast furnace slag (GGBFS). The results showed that 48 h of heat curing at 80°C was required in order to obtain similar or better performances to those of the reference 45-MPa OPC concrete. The 28-day bond strength and the overall bond stress–slip behavior of the geopolymer concrete were similar to those previously reported for OPC-based concretes. Kim and Park [26] evaluated the bond strength and development length of reinforcements embedded in geopolymer concrete with reinforcing steel using pull-out tests according to EN 10080. It was concluded that the bond strengths in geopolymer concrete decreased with the diameter of reinforcement, similar to those in ordinary concrete. Its bond were moreover greater than those in ordinary concrete. Dahou *et al*. [27] carried out RILEM-recommended pull-out tests to develop empirical models correlating the steel-concrete bond strength to the mean compressive strength of concrete for both OPC and geopolymer concretes. The developed models were compared to the existing model adopted by FIP Committee. Bond strength was investigated by conducting the tests on ribbed bars with a nominal diameter of 10 mm and/or 12 mm. The specimens were tested at various ages ranging from 1 to 28 days. Boopalan and Rajamane [28] studied the bond behaviour of reinforcing bars embedded in Fly-ash and GGBS based geopolymer concrete and conventional portland pozzolana cement concrete specimens using the pull-out tests as per Indian Standard Code IS:2770 (Part-I). It was found that the bond stress increased with the compressive strength, and the peak bond stress was about 4.3 times more than the design bond stress as per IS:456-2000. The geopolymer concretes possessed higher bond strength compared to the conventional cement concretes.

According to the aforementioned reviews, it can be observed that no study focuses on the effect of practically curing time on the bond strength between reinforcement and fly-ash geopolymer concrete. In order to bridge this gap, this paper proposes to experimentally study this effect. Various parameters are varied to compare between ordinary Portland cement (OPC) concrete and Class C fly-ash geopolymer concrete (GPC). These concretes are designed to have two different compressive strength [29], and each of them is plastic-cured in the air at 28 and 56 days. The diameter of reinforcement is selected as 12 and 16 mm with deformed type.

2 Experimental Program

2.1 *Pull-out test setup*

In this study, the pull-out test according to RILEM recommendations [30] is setup for ordinary Portland cement (OPC) concrete and geopolymer concrete (GPC) specimens. Concrete specimens with a cross section of 150×150 mm are used, and their height is varied according to the diameter of reinforcement (d_b) as shown in Figure 1. In addition, the reinforcement is located at the centre of the concrete specimen. It is observed that the embedded length of the reinforcement is equal to 5 times of its diameter according to literatures [30], [31]. The deformed bar with the diameter (d_b) of 12 and 16 mm is used as the representative for the

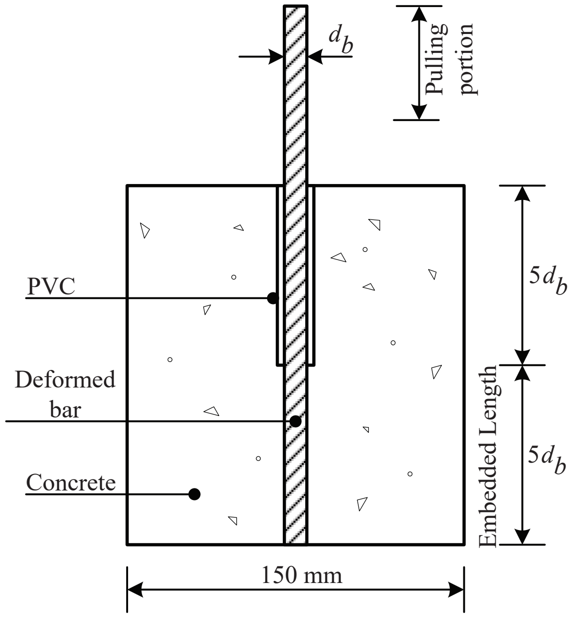


Figure 1: Pull-out test setup.

reinforcement with the tensile strength of 39 MPa. Thus, the embedded length for testing the bond strength is equal to 60 and 80 mm for 12 and 16 mm deformed bars, respectively.

2.2 *Ordinary Portland cement concrete*

The mix proportions for two different strengths of ordinary Portland cement (OPC) concrete specimens used in this study are shown in Table 1. These concretes are designed according to EIT 1008-38. These mixes use Portland type I with specific gravity of 3.15, and tap water. In addition, the fine aggregates are of river sand with fineness modulus of 2.64 and specific gravity of 2.66. The coarse aggregates are of natural rock with maximum size of 19 mm, fineness modulus of 6.35, and specific gravity of 2.7.

Table 1: Mix proportions for 1 m^3 of OPC concrete

Ingredients	OPC1	OPC2
Cement (kg)	292	373
Water (kg)	211	211
Fine aggregate (kg)	893	827
Coarse aggregate (kg)	945	945

2.3 *Fly-ash based geopolymer concrete*

The mix proportions for fly-ash based geopolymer concrete (GPC) specimens, which is developed for this study, are shown in Table 2. There are two types of geopolymer concretes according to their design compressive strength. Here, Class C fly-ash, which is a by-product from coal power plant in Mae Moh, Thailand, is used. Its basic compositions are shown in Table 3. The activator solution as a mixture of 14-M sodium hydroxide and sodium silicate is used with the ratio of a unity, according to trail mixed aiming for design compressive strength and workability in terms of geopolomer setting time. The tap water is also used in the mix. Similar to OPC, the fine aggregates are of river sand with fineness modulus of 2.64 and specific gravity of 2.66. The coarse aggregates are of natural rock with maximum size of 19 mm, fineness modulus of 6.35, and specific gravity of 2.7.

Table 2: Mix proportions for 1 m^3 of GPC

Ingredients	GPC1	GPC2
Fly-ash (kg)	292	373
14-M Sodium Hydroxide (kg)	105.5	105.5
Sodium silicate (kg)	105.5	105.5
Water (kg)	8.01	8.01
Fine aggregate (kg)	893	827
Coarse aggregate (kg)	945	945

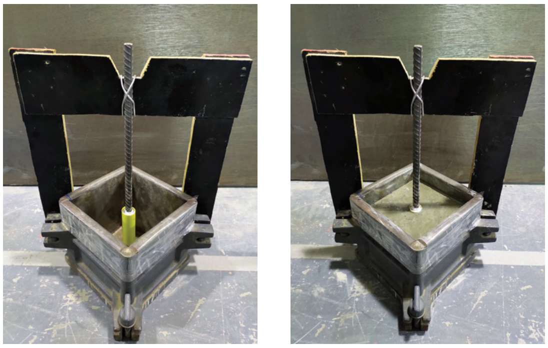
Table 3: Compositions of fly-ash in Mae Moh, Thailand

Compositions	Content (%)
SiO_2	33.4
CaO	21.5
$Al2O_3$	15
Fe_2O_3	16.5
SO_3	7.2
MgO	3.3
K_2O	2.4
Others	0.7

2.4 *Mixing, Casting, and Curing*

All specimens for pull-out and compressive strength tests are prepared in the laboratory in King Mongkut's University of Technology North Bangkok, Thailand. The deformed bars with the diameter of 12 and 16 mm are first located at the center of concrete mold as shown in Figure 2(a). After mixing, concretes are put into the mold as shown in Figure 2(b). It is noted that a plastic sheet is put between the mold and concrete for easy demolding after one day. After demolding, the specimens are plastic-cured in the air until the day of pull-out and compressive strength tests, i.e., 28 and 56 days.

Totally, 24 OPC and 24 GPC specimens are made for pull-out tests as shown in Table 4. It is noted that for each curing time period of all concrete, three concrete cylinders with the size of 100×200 mm were also cast for compressive strength test [32].



(a) Before casting (b) After casting

Figure 2: Specimen preparation.

Table 4: Pull-out test specimens

Type	Diameter of Bars (mm)	Curing Time (d)	Number of Pull-out Test Samples
OPC1	12	28	3
		56	3
	16	28	3
		56	3
OPC2	12	28	3
		56	3
	16	28	3
		56	3
GPC1	12	28	3
		56	3
	16	28	3
		56	3
GPC2	12	28	3
		56	3
	16	28	3
		56	3

Figure 3: Pull-out test on specimen.

2.5 *Pull-out loading and measurement*

On the day of pull-out tests, the specimen is carried to be set up on the universal testing machine with a capacity of 100 t as shown in Figure 3. By pulling at the top of reinforcement, the data of pull-out load and displacement are collected by a data logger.

3 Results and Discussion

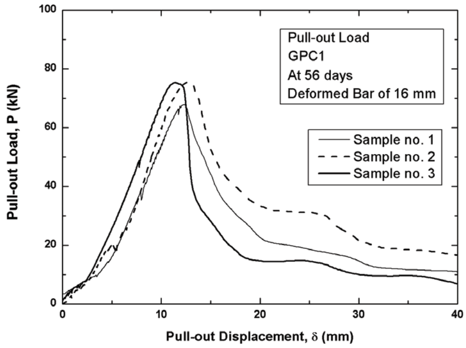
3.1 *Pull-out test results*

The data from the data logger can be plotted in terms of the relationship between pull-out load (P) and pull-out displacement (δ) measured by the universal testing machine. Figure 4(a) shows three samples of GPC1 with 16-mm deformed bar at the curing time of 56 days.

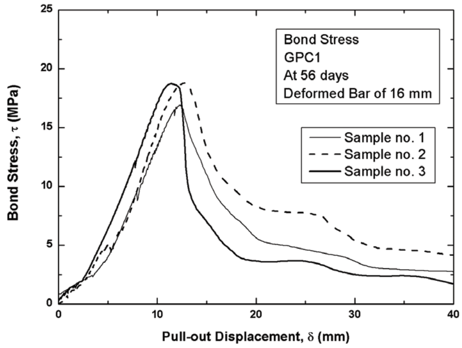
Furthermore, the relationship between the bond stress (τ) and the pull-out displacement can be calculated by dividing the pull-out load with the bonding test area, which is calculated by multiplying the perimeter of the bar with it embedded length, as [Equation (1)]

$$\tau = \frac{P}{\pi d_b l} \quad (1)$$

where d_b is the diameter of reinforcement, and l is embedded length. The bond stress of the three samples can be shown in Figure 4(b). To get the average of bond strength (u) between the reinforcement and concrete, the peak of the bond stress for all the three samples is averaged. For example, the average of the bond



(a) P-δ



(b) τ-δ

Figure 4: GPC1 with DB16 for 56 days.

strength for GPC1 embedded with 16 mm deformed bar at the curing time of 56 days is equal to 18.13 MPa. By repeating the same process, the bond strength for all OPC and GPC can be shown in Table 5.

Table 5: Bond strength for OPC and GPC

Type	Diameter of Bars (mm)	Curing Time (day)	Bond Strength, u (MPa)
OPC1	12	28	15.36
		56	18.11
	16	28	14.8
		56	15.68
OPC2	12	28	19.4
		56	25.47
	16	28	18.88
		56	20.13
GPC1	12	28	20.63
		56	21.65
	16	28	17.11
		56	18.13
GPC2	12	28	26.8
		56	33.42
	16	28	23.99
		56	29.83

3.2 *Compressive strength*

The average of the compressive strength for OPC and GPC is shown in Table 6. It is noted that, as expected, the compressive strength increases with the curing time for both OPC and GPC. Due to design mix proportions, the compressive strength of OPC1 is higher than that of OPC2, while that of GPC1 is higher than that of GPC2. Moreover, the compressive strength of GPC is higher than that of OPC. The compressive strength of OPC at 28 days is not much different from that at 56 days, because the process of cement hydration largely occurs before 28 days [33]. This also occurs with GPC, but instead the process of geopolymerisation much occurs in the early age [34].

Table 6: Compressive strength for OPC and GPC

Type	Curing Time (day)	Compressive Strength, f'_c (MPa)
OPC1	28	18.05
	56	18.34
OPC2	28	27.31
	56	27.69
GPC1	28	20.56
	56	20.85
GPC2	28	31.67
	56	33.72

Considering Tables 5 and 6, it is noted that the bond strength (u) tends to follow the following relationship given by ACI [35] as

$$u \quad \alpha \quad \frac{\sqrt{f_c'}}{d_b} \tag{2}$$

where f'_c is the compressive strength. In the other words, the bond strength is proportional directly to the square root of the compressive strength, while inversely to the diameter of reinforcement. For example, the 28 day bond strength for OPC1 and OPC2 (having the compressive strength of 18.05 and 27.31 MPa, respectively) embedded with DB12 is equal to 15.36 and 19.4 MPa, respectively. Moreover, the 28 day bond strength for OPC1 with DB12 and DB16 is equal to 15.36 and 14.8 MPa, respectively. Although these trends are observed, the effect of curing time on the bond strength is still not clear but can comparatively be determined for a clear picture of their relationship as shown in the next section.

3.3 *Comparative effect of curing time*

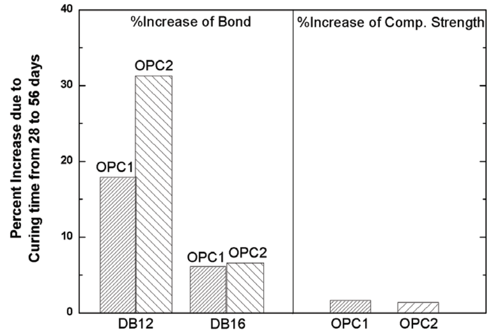
According to Tables 5 and 6, the percent increase of the bond strength ($\Delta\tau$) and the compressive strength ($\Delta f'_c$), respectively, due to the increase of curing time from 28 to 56 days can be calculated by using the following Equations (3) and (4)

$$\Delta\tau = \frac{\tau_{56} - \tau_{28}}{\tau_{28}} \times 100 \tag{3}$$

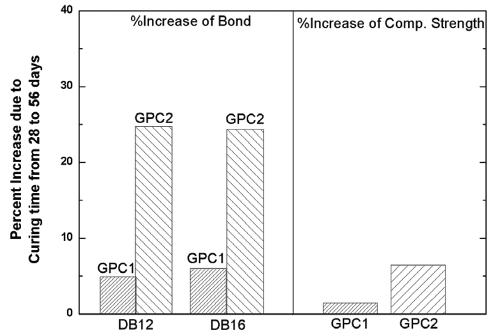
$$\Delta f_c' = \frac{f_{c,56}' - f_{c,28}'}{f_{c,28}'} \times 100 \tag{4}$$

where τ_{28} and τ_{56} mean the bond strength of both OPC and GPC at 28 and 56 days, respectively, whereas $f'_{c,28}$ and $f'_{c,56}$ mean the compressive strength of both OPC and GPC at 28 and 56 days, respectively. Using Table 5, the percent increase of the bond strength for OPC1 and GPC1 embedded with DB16 due to the increase of curing time from 28 to 56 days is, as example, calculated as 6.12% and 5.96%, respectively. Using Table 6, the percent increase of the compressive strength for OPC and GPC due to the increase of curing time from 28 to 56 days is moreover equal to 1.65% and 1.43%, respectively. Repeatedly, the percent increase of the bond and compressive strength for OPC and GPC due to the increase of curing time from 28 to 56 days can be calculated by using the same process, and the results are compared in Figure 5(a) and (b), respectively.

From the left-handed side of Figure 5(a), the percent increase of the bond strength due to the increase of the curing time for OPC1 and OPC2 with DB12 is higher than that with DB16, in spite of low percent increase of the compressive strength for OPC1 and OPC2, see the right-handed side of Figure 5(a). This shows that the bond strength of OPC with DB12 is more sensitive to the curing time than that with DB16. However, the compressive strength of OPC is not sensitive to the increase of curing time from 28 to 56 days [33]. This means that if the effect of the compressive strength does not govern, the bond strength of OPC embedded with smaller reinforcement is more sensitive to the increase of the curing time. And, the bond strength is inversely proportional to the



(a) OPC



(b) GPC

Figure 5: Percent increase of bond and compressive strengths due to curing time from 28 to 56 days.

diameter of reinforcement as shown by Equation (2). For GPC, different observations can be drawn. From the left-handed side of Figure 5(b), the percent increase of the bond strength due to the increase of the curing time for GPC2 with DB12 and DB16 is higher than that for GPC1, because the compressive strength of GPC2 is more sensitive to the increase of the curing time than that of GPC1. This means that the bond strength for GPC is not sensitive to the diameter of reinforcement, because the effect of the compressive strength governs. In particular, this occurs with GPC2 which has higher compressive strength than GPC1. And, the bond strength is directly proportional to the square root of the compressive strength as indicated by Equation (2). It is also observed that the compressive strength of GPC increase with the increase of curing time from 28 to 56 days [34].

4 Conclusions

This paper studies the effect of curing time on the bond strength between reinforcement and fly-ash geopolymer concrete. Various parameters are varied to compare between ordinary Portland cement (OPC) concrete and Class C fly-ash geopolymer concrete (GPC). From the study, it is found that

1) For both OPC and GPC, the bond strength increase with increasing the compressive strength, while with decreasing the diameter of reinforcement.

2) The bond strength of OPC embedded with smaller reinforcement is more sensitive to the increase of the curing time. But, its bond strength is not sensitive to the compressive strength, because the effect of the diameter of reinforcement governs.

3) The bond strength of GPC with higher design compressive strength is more sensitive to the increase of the curing time. However, its bond strength is not sensitive to the diameter of reinforcement, because the effect of the compressive strength governs.

4) For recommendations, concrete with higher compressive strength, such as ultra-high strength, should be further studied. Moreover, different reinforcement, such as different diameter and tensile strength, should be further considered.

Acknowledgments

This work was supported by King Mongkut's University of Technology North Bangkok, and Thailand Research Fund (TRF) under the TRF Research Career Development Grant Contract No. RSA6080049. The author would also like to acknowledge students for preparing the experiment.

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